Field Crops Research 222 (2018) 189–196

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Estimating alfalfa yield and nutritive value using remote sensing and air temperature

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ARTICLE INFO

Keywords:
Alfalfa yield
Alfalfa quality
Canopy reflectance
Growing degree units
Remote-sensing applications

ABSTRACT

In-field estimation of alfalfa (*Medicago sativa* L.) yield and nutritive value can inform management decisions to optimize forage quality and production. However, acquisition of timely information at the field scale is limited using traditional measurements such as destructive sampling and assessment of plant maturity. Remote sensing technologies (e.g., measurement of canopy reflectance) have the potential to enable rapid measurements at the field scale. Canopy reflectance (350–2500 nm) and Light Detection and Ranging (LiDAR)-estimated canopy height were measured in conjunction with destructive sampling of alfalfa across a range of maturities at Rosemount, MN in 2014 and 2015. Sets of specific spectral wavebands were determined via stepwise regression to predict alfalfa yield and nutritive value and models were reduced by spectral range to improve utility. Cumulative growing degree units (GDUs) and canopy height were tested as model covariates. An alternative GDU calculation (GDU_{ALT}) using a temporally graduating base temperature was also tested against the traditional static base temperature. The inclusion of GDU_{ALT} increased prediction accuracy for all response variables by 9–17%. Models using a common set of seven wavebands, combined with GDU_{ALT}, explained 81–90% of the variability in yield, crude protein (CP), neutral detergent fiber (NDF), and NDF digestibility (NDFd; 48-h in-vitro), respectively. This research establishes potential for remote sensing measurements to be integrated with air temperature information to achieve rapid and accurate predictions of alfalfa yield and nutritive value at the field scale for optimized harvest management.

1. Introduction

Alfalfa is the most valuable and intensively produced perennial forage crop in the United States, and precise management to achieve forage yield and quality goals is critical to optimize profitability (Bouton, 2007). Indices of nutritive value such as relative forage quality (RFQ) can decline up to 5 index points per day (Undersander et al., 2010), which equates to an economic loss of 4–8 USD Mg alfalfa^{-1} d^{-1} in hay value (Szafranski and Martens, 2017), or a dairy productivity loss of approximately 25 kg milk Mg^{-1} d^{-1} (Undersander et al., 2016). These implications on economic value and animal productivity necessitate accurate in situ estimations of alfalfa yield and nutritive parameters. Furthermore, pre-harvest insight to nutritive value and yield can enable real-time management responses to fluctuating market conditions or feed needs. Therefore, methods capable of rapid and accurate predictions at the field-scale are needed to improve the economic efficiency and resilience of alfalfa production.

Several methods have been reported for in situ estimations of alfalfa yield and nutritive value. These include estimations based on 1) air temperature quantified as Growing Degree Units (GDUs), 2) alfalfa morphological development, and 3) remote sensing measurements. Maturity-based estimations are seldom representative of an entire field;

Abbreviations: ADF, acid detergent fiber; CARI, Chlorophyll Absorption Ratio Index; CP, crude protein; GDU_{base-5}, cumulative growing degree units since last alfalfa harvest (base temperature = 5 °C); GDU_{ALT}, cumulative growing degree units since last alfalfa harvest base temperature graduating from 3.5 °C (1 April) to 10 °C (31 July) and static at 10 °C through the remainder of the year; GNDVI, Green Normalized Difference Vegetation Index; MSC, mean alfalfa stem growth stage by count; MSW, mean alfalfa stem growth stage by weight; MTCI, MERIS Terrestrial Chlorophyll Index; NDF, neutral detergent fiber; NDFd, neutral detergent fiber digestibility (48-h in-vitro); NDLI, Normalized Difference Lignin Index; NDNI, Normalized Difference Nitrogen Index; NDVI, Normalized Difference Vegetation Index; NIR, wavebands within the near-infrared region of the electromagnetic spectrum (751–1100 nm); PRI, Photochemical Reflectance Index; REIP, Red Edge Inflection Point; SWIR, wavebands within the near-infrared region of the electromagnetic spectrum (1101–2500); UTILITY, set of seven common wavebands identified to predict all four dependent variables; VIS, wavebands within the visible region of the electromagnetic spectrum (350–750 nm)

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https://doi.org/10.1016/j.fcr.2018.01.017
Received 17 August 2017; Received in revised form 14 January 2018; Accepted 15 January 2018

whereas remote measurement of canopy reflectance can achieve rapid, direct assessment of a crop at field scale. However, the costs of these technologies are currently prohibitive in on-farm applications. The cost of spectral measurement technology increases with greater spectral range and resolution of the instrument. Therefore, applications may be developed that use fewer wavebands at lower spectral resolution, and may be combined with environmental data such as air temperature to improve the affordability and utility of these technologies.

Cumulative GDUs have been used previously to estimate both alfalfa yield (Smeal et al., 1991) and nutritive value (Kratchunov and Naydenov, 1995; Sulc et al., 1999). Traditional GDU calculations for alfalfa use a static base temperature (T_b) of 5 °C; however, Sharratt et al. (1989) reported that the optimum T_b for alfalfa may change throughout the growing season from 3.5 °C early in the growing season to 10 °C later in the summer. Predictions of nutritive value based only on cumulative GDUs have limited accuracy (Sulc et al., 1999), but the use of a modified GDU scale has not been investigated for predictions of alfalfa nutritive value. Advantages of using air temperature are that it is generally free and easily accessible, and that applications can be automated to use real-time information.

Visual estimations of morphological development were traditionally used to decide timing of harvest. For example, the decision to harvest alfalfa may be made when a visual assessment determines that 10% of the plants are flowering. To improve the accuracy of these estimations, Kalu and Fick (1981) assigned a numeric scale to distinct growth stages. Indices are calculated as the average growth stage weighted by number of stems [mean growth stage by count (MSC)] or plant mass within each maturity group [mean growth stage by weight (MSW)]. Kalu and Fick (1983) found that MSW provided accurate predictions of alfalfa CP, NDF, acid detergent fiber (ADF), and lignin with R^2 ranging 0.84–0.95. Hintz and Albrecht (1991) showed that predictions based on node number and plant height can provide more rapid predictions with accuracy similar to or greater than MSC and MS Owens et al. (1995) reported that using the PEAQ (Predictive Equations for Alfalfa Quality) system based on maturity of the most mature stem, along with the height of the tallest stem, provided accurate estimates of NDF and ADF (R^2 = 0.72), but are less predictive for CP (R^2 = 0.37). Additionally, Lyons et al. (2016) showed potential for alfalfa height to predict yield (R^2 = 0.66). These methods have been consistently demonstrated as valuable indicators, although it is difficult to accurately represent an entire field using contact measurements, considering time and labor requirements. Furthermore, the accuracy of these methods may vary across environmental conditions (Sanderson, 1992) and may not be applicable to new reduced-lignin alfalfa cultivars.

Remote sensing technologies include measurement of canopy reflectance, infrared measurement of canopy temperature, and LiDAR- or SONAR-based estimates of height. Precision crop management tools such as remote sensing are being developed and implemented in many crops as technology becomes more affordable and specific applications are developed (Mulla, 2013). Spectral vegetative indices (SVIs) are functions of canopy reflectance developed to assess ground cover, crop health, drought stress, and nutrient deficiencies in several major crops. These remote sensing tools can be integrated into Unmanned Aerial Vehicle (UAV) platforms to enable real-time assessments of crop nutritive value parameters at the field scale (Zhang and Kovacs, 2012). Recent research has demonstrated the potential for measurement of canopy reflectance to predict nutritive value in alfalfa monocultures (Starks et al., 2016) and perennial forage grasses (Starks et al., 2006). Starks et al. (2016) report predictions based on canopy reflectance to explain 77–83% of variation in CP, NDF, and ADF. In addition to measurement of canopy reflectance, ultra-sonic or LiDAR technology can enable remote measurement of crop height and facilitate improved estimations of crop biomass (Pittman et al., 2015). Additionally, crop height is related to alfalfa nutritive value (Owens et al., 1995). However, these technologies have not been integrated into applications to inform harvest decisions and their efficacy has not been compared to predictions based on morphological development or GDUs.

These methods of in situ crop assessment vary in accuracy and utility. The development and efficacy of models using simplified remote measurements requires further investigation, and these remote sensing approaches have not been tested in combination with temperature-based estimations. This research explores the potential for simplified remote sensing tools integrated with environmental data for more affordable applications. The objectives were to 1) develop a method for selecting specific canopy reflectance wavebands to estimate alfalfa yield and nutritive value, 2) determine the predictive value of reduced models that use fewer parameters, 3) compare utility of remote estimations to traditional assessment methods based on phenological stage and GDU accumulation, and 4) test the value of integrating environmental information such as air temperature with canopy reflectance and remotely-estimated canopy height. Our hypotheses were that 1) a set of specific wavebands of easily measureable range and resolution can be identified and used to predict alfalfa yield and nutritive value in situ, 2) the accuracy of these remote estimations will be comparable to traditional assessment methods, and 3) the integration of environmental growth indicators (cumulative GDUs) with remote measurements can provide greater prediction accuracy than these methods used alone.

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in 2014 and 2015 at the University of Minnesota Research and Outreach Center in Rosemount, MN (44°42′37.34″N 93°06′10.61″W) on a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). Sites were fertilized with potassium (K) and sulfur (S) according to soil requirements for alfalfa production (Kaiser et al., 2011), and irrigated to meet monthly average precipitation levels. Air temperature and precipitation data were obtained from a weather station located within < 1 km of the experiments.

Data were collected from three different fields of alfalfa at varying times throughout the study (Table 1). Each alfalfa stand had sufficient plant density for optimum production (> 50 plants m^{-2}) (Sheaffer et al., 1988) which was determined by counting plants in a m^2 quadrant at four random locations from each of the sites. In 2014, all alfalfa was cut at a height of 5 cm above the soil and removed from the plot areas (30 × 38 m) on 31 July. Each site was divided into a completely randomized design with four replications and 16 plots (1.8 × 4.6 m) per replication. Measurements of canopy reflectance were recorded in conjunction with destructive sampling on 3- to 4-d intervals. At each sampling event, one plot in each replication was sampled and each plot was sampled only once, resulting in 16 sampling dates.

The experimental design was modified in 2015 to include 12 replications with 10 plots (1.8 × 1.8 m) per replication. All alfalfa was cut at a height of 5 cm above the soil and removed from one plot per replication on 3- to 4-d intervals for 10 harvest dates, resulting in a range

Table 1
Experimental site descriptions and sampling timeline.

Year	Growth period sampled	Alfalfa variety	Year planted	Site ID	Replications per site
2014	15 Aug–15 Oct	Dekalb ‘4401-RR’	2013	1	4
	15 Aug–15 Oct	Pioneer ‘55V12’	2012	2	4
2015	15 Apr–16 Jun	Dekalb ‘4401-RR’	2013	1	12
	3 Jul–20 Aug	Dekalb ‘4401-RR’	2013	3	12